Pressable Glass-Ceramics With Textured Microstructure

Cross-Reference to Related Applications:

This application claims priority to U.S. Provisional Application No. 60/436,202, filed December 23, 2002, which is incorporated herein by reference.

Field Of Invention

This invention relates generally to glass-ceramics comprising leucite and more specifically to glass-ceramics for use in the manufacture of dental restorations and methods of manufacture thereof.

Background Of The Invention

High-strength feldspathic dental porcelains were first introduced in the dental industry in the 1980s. Optec™ porcelain, the subject of U.S. Patent No. 4,798,536, is one example of feldspathic porcelain that has been used in the manufacture of all-ceramic dental restorations. Currently, the most common technique for manufacturing all-ceramic dental restorations is heat-pressing, also known as injection molding, of all-ceramic cores. Dental glass-ceramic materials, such as OPC® pressable ceramic and Empress® pressable ceramic, exhibit flexure strength from about 120 MPa to about 180 MPa due to a relatively high fraction of leucite crystals embedded in the glass matrix. Historically, the first leucite-containing components of dental porcelains were produced by melting potassium feldspar with fluxes as described in U.S. Patent No. 4,798,536, which is hereby incorporated by reference. Thus, these glass-ceramic materials are often also referred to as high-strength feldspathic dental porcelains or leucite-reinforced dental ceramics or glass-ceramics. The leucite content in these materials is higher than at least about 35 weight percent and most of the porcelains have a leucite content from about 45 to about 60 weight percent. As a result, they exhibit relatively high coefficients of thermal expansion (CTE) in excess of about 15 x 10^{-6}/°C (from room temperature to 500°C) and require specifically developed porcelains with a matching high thermal

expansion. At the same time, most of the porcelains used for porcelain-fused-to-metal (PFM) restorations have CTEs of about 12 to about 13 x 10^{-6}/°C (from room temperature to 500°C) and are compatible with most commonly used precious and non-precious alloys having CTEs in the range of about 13 to about 15 x 10^{-6}/°C (from room temperature to 500°C). Thus, these porcelains are commonly referred to as conventional porcelains.

One of the distinct advantages of the heat-pressing (injection molding) method for fabricating all-ceramic cores is exceptionally accurate and consistent margin adaptation. Only very few and the most experienced dental technicians can achieve the same accuracy building porcelain margins by hand. The most time-consuming procedure is manual fabrication of porcelain margins on multi-unit metal frameworks for fixed partial dentures (FPD) or bridges. To circumvent these difficulties, a new method commonly referred to as "pressing to metal" was recently introduced, where a heat-pressing technique is used to press high expansion leucite-based glass-ceramic directly onto a metal framework. As a result, to produce the finished restoration, the technique requires layering the press-to-metal core with the porcelain having a coefficient of thermal expansion exceeding that of conventional porcelains.

It would be extremely beneficial to have pressable all-ceramic cores compatible with these aforementioned porcelains and at the same time capable of being directly pressed to metal.

Summary Of The Invention

These and other objects and advantages are accomplished by the pressable dental ceramic of the present invention comprising a mixture of glass and glass-ceramic frits. A refractory filler is also combined with the frits. The dental ceramic contains an amount of leucite less than about 35 percent by weight. Other additives may be included such as pigments, opacifying agents and fluorescing agents. Prior to pressing, the dental ceramic comprises a cellular-like microstructure comprised of glassy regions surrounded by clusters of leucite crystals distributed around those glassy regions forming a cellular three-dimensional network and after pressing, the dental material comprises a textured microstructure.

In another embodiment, a pressable dental ceramic is formed by mixing and firing at least one glass frit and at least one glass-ceramic frit. Preferably, pellets or blanks are fabricated by mixing two frits, a relatively coarse glass frit and a very fine leucite-containing frit. Specifically, the average particle size of the leucite frit should be about six times smaller than the particle size of the glass frit. The pressable pellet exhibits a cellular-like microstructure comprised of glassy regions surrounded by clusters of leucite crystals distributed around those glassy regions forming a cellular three-dimensional network, which transforms into a textured microstructure upon pressing.

The pressable dental ceramics are useful for forming cores and frameworks for all ceramic dental restorations and as overlays for press-to-metal dental restorations including, but not limited to, orthodontic appliances, bridges, space maintainers, tooth replacement appliances, splints, crowns, partial crowns, dentures, posts, teeth, jackets, inlays, onlays, facing, veneers, facets, implants, abutments, cylinders, and connectors.

Brief Description Of The Drawings

Features of the present invention are disclosed in the accompanying drawings, wherein similar reference characters denote similar elements throughout the several views, and wherein:

FIGURE 1 is a photomicrograph of the dental ceramic prior to pressing;

FIGURE 2 is a schematic diagram of the photomicrograph of FIGURE 1;

FIGURE 3 is a photomicrograph of the dental ceramic of FIGURE 1 after pressing;

FIGURE 4 is a schematic diagram of the photomicrograph of FIGURE 3;

FIGURE 5 shows thermal expansion curves for three different materials;

FIGURE 6 shows an enlarged view of a section of the schematic diagram shown in FIGURE 4; and

FIGURE 7 shows a magnified section of an area in the photomicrograph of FIGURE 1.

Description Of The Invention

Leucite-based glass ceramic materials of the present invention are made by a

conventional heat-pressing technique, also known as injection molding, similar to procedures used to manufacture OPC® pressable ceramic available from Pentron Laboratory Technologies, LLC and Empress® pressable ceramic available from Ivoclar Corporation. In order to press cores for all-ceramic dental restorations using these conventional techniques and commercial equipment, the materials are formed into the shape of a blank or pellet. Blanks or pellets are fabricated by compacting and subsequently firing starting glass-ceramic powder comprising a mixture of various glass or glass-ceramic frits and additives such as pigments, opacifying agents and fluorescing agents. The essential feature of the present invention is that these blanks/pellets have a cellular-like microstructure comprised of glassy regions surrounded by clusters of leucite crystals distributed around those glassy regions forming a cellular three-dimensional network.

In one embodiment herein, a pressable dental ceramic pellet or blank is formed from a mixture of at least one glass frit, at least one glass-ceramic frit and at least one refractory filler. Preferably, the glass frit is present in an amount of from about 40 to about 65 percent by weight, the glass-ceramic frit is present in an amount of from about 35 to about 60 percent by weight and the refractory filler is present in an amount from about 0.5 to about 10 percent by weight. The glass-ceramic frit contains an amount of leucite of at least 60 percent by weight to provide an amount of leucite in the final dental ceramic composition of less than or equal to about 35 percent by weight.

The role of the refractory filler is two-fold. It is needed to lower the thermal expansion of the porcelain and also to impart enough resistance to distortion to enable preserving accurate fit and marginal integrity during repetitive firing of the overlay porcelain onto the dental ceramic. Normally, the difference between the pressing temperature for a pressable core and the firing temperature of the overlay porcelain is at least 150°C. By contrast, in the invention herein, the difference between the pressing temperature for the pressable core and the firing temperature of the overlay porcelain is less than about 150°C and preferably less than about 110°C. Materials of the present invention are pressable at temperatures as low as 980°C, but due to both their textured microstructure and the presence of the refractory filler, they can withstand the firing of the overlay porcelain thereon to temperatures as high as 900°C (1652°F), which is a small

difference of 80°C.

The textured microstructure provides integrity to the dental ceramic and the refractory filler prevents distortion of the dental ceramic. In order to provide optimum results, the refractory filler should have a thermal expansion lower than the thermal expansion of the frits used in the pressable core material and a refractive index within about 0.2 of the refractive index of the frits. Opacifiers, such as zirconia, titania, zirconium silicate (ultrox) and tin oxide, which are conventional additives in dental ceramic and porcelain materials are different from the refractory fillers used herein because they are used to opacify the frits and must have a refractive index that is different from the refractive index of the frits by 0.5 or greater in order to opacify. Glass and glass ceramic frits have a refractive index in the range from about 1.45 to about 1.55, which is characteristic of most conventional alumo-silicate and alumo-boro-silicate glasses. The following Table 1 provides the refractive indices of various opacifers, glass and glass-ceramic frits and refractory fillers of the invention.

Table 1. Refractive Indices.

Material	Crystal Structure	Refractive Index	Use	Difference In RI Between Frits And Material
TiO2	Rutile	2.7	Opacifier	1.2
ZrO2	Mg-Stabilized Zirconia (Cubic And Tetragonal)	2.15	Opacifier	0.65
SnO2	Casseterite	2.093	Opacifier	0.593
ZrSiO4		1.95	Opacifier	0.45
Al2O3	Corundum	1.76	Opacifier	0.26
ZnO		2.01	Opacifier	0.51
Glass and Glass-Ceramic Frits		1.45 – 1.55		0
leucite		1.5		0
Cordierite		1.53	Refractory Filler	0.03
Mullite		1.64	Refractory Filler	0.14
Spinel		1.72	Refractory Filler	0.22
Alumina		1.76	Can Be Used As Refractory Filler Only In Combination With Others	0.26

Fused (amorphous) silica		1.46	Refractory Filler	0.04
Quartz (crystalline silica)		1.55	Refractory Filler	0.05

Prior to pressing the dental ceramic blank or pellet into a dental restorative material, the dental ceramic comprises a cellular-like microstructure comprised of glassy regions surrounded by clusters of leucite crystals distributed around those glassy regions forming a cellular three-dimensional network. Figures 1, 2 and 7 clearly represent this aspect of the dental ceramic.

In yet another embodiment, at least one glass frit is mixed with at least one glass-ceramic frit and sintered to form a pressable dental ceramic. Preferably, pellets are fabricated by mixing two frits, a relatively coarse glass frit and a very fine leucite-containing frit. Opacifying agents, fluorescing agents, other additives and pigments may be added to the mixture as well. The particle size distribution of the component frits are engineered specifically to ensure that during the blending of the frits and compacting the resulting mixture into the shape of pellets, the leucite frit will be coordinated into interstitial sites between much larger particles of the glass frit. Specifically, the average particle size of the leucite frit should be about six times smaller than that of the glass frit. More specifically, the average particle size (mv) of the leucite frit should be less than about 7 microns (mμ) and the average particle size (mv) of the glass frit should be more than about 35 mμ. It is most preferred that the leucite frit has an mv $\leq$6 mμ and the glass frit has an mv $\geq$36 mμ.

The pressing temperature of the dental ceramics discussed herein is from about 980 to about 1030°C. After pressing the dental ceramic into a mold whereby it is formed into the desired shape, it is able to withstand firing of a porcelain thereon at a range from about 830 to about 900°C without distorting the dental ceramic.

Figure 1 represents a micrograph of the microstructure of a pellet (from Example 1 below) manufactured in accordance herein comprising a three-dimensional network of leucite arranged in a cellular pattern and Figure 2 shows a schematic diagram of the micrograph of Figure 1. Figure 2 depicts leucite-containing sections 20 separated by glassy, leucite-free sections 22. During pressing, the roughly equiaxed "cells" of the

cellular microstructure are being stretched in the direction of viscous flow and flattened in the direction normal to the flow which results in a so-called "pancake" structure as shown in Figures 3 and 4.

Figure 3 is a micrograph of the pellet from Figure 1 that has been pressed at 1020°C and Figure 4 is a schematic diagram of the micrograph of Figure 3. Figure 4 shows leucite-containing layers 40 separated by glassy, leucite-free layers 42. This "pancake" structure is well known in metallurgy as a type of structure formed by cold-working of metals. In the case of metals this "pancake" microstructure is formed by plastic deformation of the originally equiaxed grains and results in a stronger metal, an effect known as strain-hardening. In the glass-ceramic material of the present invention, somewhat similar microstructural changes resulting in a pancake appearance of the microstructural features (cells) are achieved by constrained viscous flow of the glass-ceramic material forced through narrow channels of the refractory mold.

This coordination between particle sizes of the component frits results in a cellular microstructure (as shown in Figures 1 and 2) in the pellet, which upon pressing transforms into a "pancake" or layered type of microstructure (as shown in Figures 3 and 4). The inventor herein has found that this combination produces surprisingly high strength and, at the same time, relatively low expansion. In the following description, the term "layered" is used interchangeably with the term "textured" to describe the generic type of microstructure associated with the materials described herein.

Figure 6 shows an enlarged section of individual leucite crystals from Figure 4. The schematic diagram shown in Figure 2 would render the same depiction of individual leucite crystals as shown in Figure 6. Figure 7 shows a magnified section of an area in the dental ceramic shown in Figure 1. It shows individual leucite crystals that are schematically shown in Figure 6.

The following examples illustrate the invention.

Example 1 and Comparative Example 2

To illustrate the concept of the textured microstructure, two examples were carried out having the same composition, but with different particle sizes. Two frits with compositions and properties given in Table 2 below were mixed with a small amount of

an opacifier and hand-pressed into cylindrical pellets. A first glass frit (a low expansion frit) with a CTE of about 9 x 10^{-6}/°C (from room temperature to 500°C) was added as approximately 57 wt% of the mixture. A second, high expansion frit, containing about 60% to about 70% of leucite with a CTE of about 18 x 10^{-6}/°C (from room temperature to 500°C) was added as approximately 40% of the mixture. Additionally, about 3 wt% of Al_2O_3 was added as a refractory filler (alumina is used for the sake of illustration of the concept since it has refractive index that is a bit too high to use in substantial quantity without over opacifying the material). The high expansion frit was fabricated in two particle size variations, fine with average particle size of about 6 mμ and coarse with average particle size of about 18 mμ. The fine frit was used in Example 1 and the coarse frit was used in comparative Example 2. The same glass frit with an average particle size of about 33 mμ was used in both examples. Component frits and alumina were mixed and dry-pressed into small cylindrical pellets weighing approximately 2 grams each. Pellets of Example 1 and Example 2 were fired in vacuum to full density using the same firing cycle. Various dental articles as well as rods for 3-pt bending were pressed into refractory molds made from Universal™ Investment material using a conventional pressing technique in the AutoPress® Plus pressing furnace (available from Pentron Laboratory Technologies, LLC) at 1020°C. Rods were tested in 3-pt bending equipment. The material of Example 1 with the layered pancake microstructure exhibited a flexure strength of 137±12 MPa and the material from comparative Example 2 having an equiaxed microstructure exhibited a flexure strength of 92±5 MPa.

Table 2. Component frit compositions and properties

	Glass Frit	Leucite Frit	Overall Composition of Example 1 and Comparative Example 2
CTE@500°C, ppm=10^{-6} (°C)$^{-1}$	9	18	13.3
Glass Transition Temperature	600	650	610
Average particle size, μm	33	6 (Example 1) 18 (Example2)	
SiO2	67.93	65.01	64.69
B2O3	0.00	0.00	0

Al2O3	13.35	18.01	17.79
ZnO	0.00	0.00	0
CaO	1.99	0.77	1.44
MgO	0.00	0.00	0
BaO	0.00	0.00	0
Li2O	0.00	0.51	0.2
K2O	10.16	13.89	11.34
Na2O	6.18	1.81	4.24
TiO2	0.00	0.00	0
ZrO2	0.00	0.00	0
CeO2	0.40	0.00	0.28

Example 3

The same glass as the one used in Examples 1 and 2 in Table 2 above was milled to yield a glass (a low expansion) frit with an average particle size of 36 μm. The high expansion frit of Examples 1 and 2 was combined with a second high expansion frit in the weight ratio of from 1:1 to 1:1.5. Both high expansion frits had a particle size of about 6 μm. The mixture of the two high expansion frits was combined with the glass frit in the ratio of about 1:1. Additionally, about 2 wt% of Al_2O_3 and about 2 wt% of fused silica were added to lower the thermal expansion of the mixture of the frits and to impart sufficient resistance to distortion to enable firing of the overlay porcelain at temperatures up to about 890°C.

Table 3. Overall composition of Example 3 and Example 1 & 2 from above.

			Frits Used in Example 3		
Overall composition, wt%	Examples 1&2	Example 3	Glass Frit	First Leucite Frit	Second Leucite Frit
SiO2	64.69	65.37	67.39	65.01	63.82
B2O3	0.00	0.00	0.00	0.00	0.00
Al2O3	17.79	17.03	13.35	18.01	17.69
ZnO	0.00	0.00	0.00	0.00	0.00
CaO	1.44	1.30	1.99	0.77	0.76
MgO	0.00	0.00	0.00	0.00	0.00
BaO	0.00	0.00	0.00	0.00	0.00
Li2O	0.20	0.67	0.00	0.51	1.88
K2O	11.34	11.54	10.16	13.89	13.67

Na2O	4.24	3.74	6.18	1.81	1.77
TiO2	0.00	0.00	0.00	0.00	0.00
ZrO2	0.00	0.00	0.00	0.00	0.00
CeO2	0.28	0.35	0.40	0.00	0.41

Pellets were fabricated as described in Examples 1 and 2 above. Heat-pressing was carried out at 990°C using the same equipment and procedures as in the previous examples. A plastic rod with a length of 63 mm was invested in a 300 g investment ring. Following burn-out, pressing and divesting, the as-pressed rod was cut to 51 mm and used to measure thermal expansion from room temperature to 700°C. The CTE was measured as 13.6 x 10^{-6}/°C and 14.0 x 10^{-6}/°C (from room temperature to 500°C and to 600°C, respectively), and the GTT was 570°C±20°C measured at as-pressed condition. Figure 5 shows thermal expansion curves of the pressed glass-ceramics of Examples 1 and 3 overlaid with thermal expansion curves of Avante Micro Crystal® body and incisal porcelain. Some of the pressed samples were sectioned, mounted, polished and etched for microscopic examination to confirm the presence of a textured microstructure as shown in Figures 3 and 4.

Example 4

Strength, Weibull Modulus And Compatibility With Porcelain-Fused-To-Metal (PFM) Porcelain

A mixture of frits used in Example 3 and fused silica was shaded by using about 1% of commercially available pigments. Pellets were fabricated as described above in the previous examples. Various dental articles and various test specimens including 24 rods for a 3-pt bend test were pressed at 1000°C using the equipment and procedures described above. Following normal divesting procedures, as-pressed rods of about 20 mm in length and about 3.3 mm in diameter were loaded to failure in three-point bending configuration. Three-point flexure strength was determined to be 142 MPa with a standard deviation as low as 12 MPa (8.4%). In addition, the measured strength values were ranked and used to calculate the Weibull modulus (m). An extremely high Weibull modulus of 13.6 and a Weibull strength value (σ_o) of 146.9 MPa with the correlation factor (R^2) of 0.95 were established for this material. Based on the determined Weibull

parameters, a stress value corresponding to the survival probability of 99.9%, ($\sigma_{99.9\%}$) (representing the case when only one specimen in 1000 fails) was calculated to be 88.5 MPa. Both values for Weibull modulus (m), and $\sigma_{99.9\%}$ were surprisingly high compared to values for leucite-containing, lithium disilicate and glass infiltrated dental ceramics known from the literature (H. Fisher, M. Weber, and R. Marx, Lifetime Prediction of All-ceramic Bridges by Computational Methods, *J Dent Res* 82 (3): 238-242, 2003) which is hereby incorporated by reference and which results are summarized in Table 4 below. Most important, the $\sigma_{99.9\%}$ of 88.5 MPa was substantially higher than the maximum principal stress of 72 MPa associated with peak loads produced during the normal masticating process. This data indicates the specific benefits associated with a type of microstructure, termed layered or textured, characteristic for glass-ceramic materials of this invention. The leucite-based glass-ceramics of this invention having leucite content of less than 35% still exhibits strength comparable to leucite-reinforced dental ceramics such as Empress® and OPC® which have higher leucite content. At the same time, in reliability, it matches much stronger and tougher ceramic materials such as some lithium disilicate and glass infiltrated ceramics (see Fisher et al. for m values for these materials).

Table 4. Data from Fisher Article and from Example 3 herein.

Material	Type of Glass-Ceramic	Elastic Modulus GPa	Poisson's Ration v	σ_0 MPa	Weibull Modulus m	Calculated $\sigma_{99.9\%}$	$\sigma_{1,max}$ MPa @ 600 N load	Reliability Factor = $\sigma_{99.9\%}/\sigma_1$
Empress®1*	leucite	67	0.19	89	8.6	40	72	0.55
Empress®2*	lithium-disilicate	96	0.22	289	8.8	132	85	1.55
InCeram™ Alumina**	glass-infiltrated	251	0.22	290	4.6	65	130	0.50
3Y-SZ™***	YTZP zirconia	205	0.31	937	18.4	644	125	5.15
Example 3	leucite	70	0.2	146.9	13.6	88	72	1.23

*IVOCLAR AG CORPORATION
**VITA ZAHNFABRIK H. RAUTER GMBH & CO.
***METOXIT AG

A number copings and nearly full contour crowns were pressed at temperatures of varying from 980°C to 1000°C to evaluate fit and absence of distortion from both white (unshaded) and shaded material. The pressed copings were layered with Avante Microcrystal® porcelain (Pentron) and d.SIGN® porcelain (Ivoclar). Both porcelains are currently used to fabricate PFM restorations using alloys with a CTE of about 13-15 x 10^{-}

^{6}/°C. Porcelains were fired at temperatures of varying from 830°C to 900°C with grinding and the addition of new porcelain for up to four times. No distortion, cracking, crazing or discoloration was observed.

A standard master die was used to design a standard framework for a 4-unit posterior bridge with up to 4 mm long margins. This standard framework was duplicated in a variety of metals including Rexillium III®, Rexillium® V, REX 4®, REX CC® and Avante MicroFine™ 50, 60, 68, 76 alloys and Rx G-Universal. Following application of two coats of Avante® Opaque these frameworks were invested in 300 g rings often together with wax-ups for all-ceramic single units. Shaded pellets of the glass-ceramic composition of Example 3 were pressed at 1000°C. Following standard divesting and cleaning procedures the press-to-metal bridges were layered with Avante Microcrystal® and d.SIGN® porcelains and fired with grinding and addition of new porcelain for up to four times. No distortion, cracking, crazing or discoloration was observed.

The essential feature of the glass-ceramic material of this invention is its engineered microstructure that results in a relatively high strength at low leucite content and therefore a relatively low CTE in the range of 12.5 – 14.5 ppm. As a result, all-ceramic cores made from this material are compatible with some porcelains used in PFM restorations fabricated on a wide range of popular and commonly used alloys having a CTE in the range of 13 – 15 ppm. The material of the present invention can be pressed onto metal directly.

While various descriptions of the present invention are described above, it should be understood that the various features can be used singly or in any combination thereof. Therefore, this invention is not to be limited to only the specifically preferred embodiments depicted herein.

Further, it should be understood that variations and modifications within the spirit and scope of the invention may occur to those skilled in the art to which the invention pertains. Accordingly, all expedient modifications readily attainable by one versed in the art from the disclosure set forth herein that are within the scope and spirit of the present invention are to be included as further embodiments of the present invention. The scope of the present invention is accordingly defined as set forth in the appended claims.